Science Robotics AAAS

Manuscript Template

FRONT MATTER

3D-printed passively variable transmission for high speed and force applications shown in a lightweight, tendon driven prosthetic hand.

Title

- Elastomeric Passive Transmission for Autonomous Force-Velocity Adaptation Applied to 3D Printed Prosthetics
- The Elastomeric Passive Transmission

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Summary

3D-printed passively variable transmission for high speed and force applications shown in a lightweight, tendon driven prosthetic hand.

Abstract

The force, speed, dexterity, and compact size required of prosthetic hands presents an extreme design challenge for engineers. Current prosthetics rely on high-quality motors to achieve adequate precision, force, and speed in a small enough form factor with the tradeoff of high cost. In this work, we present a simple, compact, and cost-effective continuously variable transmission (CVT) produced via projection stereolithography. Our transmission, which we call an Elastomeric Passive Transmission (EPT), is a polyurethane composite cylinder which autonomously adjusts its radius based on the tension in a wire spooled around it. We integrated six of these EPTs into a 3D-printed soft prosthetic hand with six active degrees of freedom. Our EPTs provide the prosthetic hand with ~3X increase in grip force without compromising flexion speed. This increased performance leads to finger closing speeds of ~0.5 seconds (Γ~180 degrees s^{-1}) and maximum fingertip forces of ~32 N per finger.

MAIN TEXT

Introduction

The grip strength, grasping speed, and active degrees-of-freedom of even the most advanced prosthetic hands pale in comparison to those of a human. Developing prosthetic limbs requires designers to make difficult trade-offs between the size, weight, force, speed, and cost of the actuation system (1). User studies have shown that 90% of patients with myoelectric prostheses consider their prosthetic hand to be too slow and 79% consider it to be too heavy (2). Based on this user feedback, it is easy to see why state-of-the-art prosthetic hands such as the BeBionic Hand (Ottobock; ~$11,000) and the iLimb (Touch Bionics, Inc.; ~$18,000) rely on high quality motors such as the Faulhaber 1024SR (~$200) to achieve the necessary precision, torque, and speed in a small enough form factor (3). Lower performing motors of similar size (e.g., Pololu micrometal gearmotors) (4, 5), are significantly lower in cost (~$15) but require choosing between applying sufficient force or speed to the prosthetic. Examples of prosthetic hands that use low-cost motors are Open Bionics, Inc. (Brunel Hand; ~$1,500) (6), and open-source initiatives such as OPENBIONICS (~$200) (7-9). The combination of speed and strength of these powered hands is limited due to the use of less costly motors, as well as the materials from which they are composed (i.e., acrylic, TPU, and PLA).

A good solution to this classic engineering contradiction of speed vs. force is to dynamically adjust the motor's effective gearing ratio. Many of the systems used to accomplish this dynamic adjustment, such as the Passively Variable Transmission (10), load-sensitive Continuously Variable Transmission (CVT) (11), and the Adjustable Power Transmitting Mechanism (12) use jointed mechanisms. Another system, demonstrated by Belter et al., uses a variable pitch roller to adjust the angle at which a string spools around a cylindrical rod (13). Work from Shin et al. uses dual-mode twisting of strings to provide high speed in one configuration and high force in the other (14). Matsushita et al. developed a drum CVT which changes the radius at which a string spools around a cylinder by compressing a spring in the center of the transmission (15). Felton et al. demonstrates an origami-inspired CVT wheel, whose dodecahedral fold pattern allows for the radial compression of reinforced faces to modulate transmission ratio (16). Though each of these systems have their merits, they are limited by their size, complexity, fabrication techniques and material requirements. These same requirements preclude 3D printing them for compact and custom prosthetics.

In this paper, we report a simple, low-cost, 3D-printed CVT system using elastomeric material. These Elastomeric Passive Transmissions (EPTs) are, essentially, rubber wheels mounted on a rotary motor that spool a wire—they continuously decrease their moment arm as additional load is applied. At no load, they have a large radius and spool quickly for fast actuation but apply less total force as the moment arm is larger. At high load, their radius is passively minimized so they spool more slowly and apply higher forces (Fig. 1a). EPTs, as spring-like components between the motor and actuator (finger), act as series elastic elements which have been shown to assist in shock tolerance, improved force control, and reduced reflected inertia (17, 18).

Many prosthetic hands and robotic grippers have been designed using tendon-driven actuators (19-30). To demonstrate the capabilities of our EPTs, we used them to fabricate a six degree of freedom (DOF) tendon-driven prosthetic hand that displays an excellent combination of gripping speed and strength, at a low cost. We utilize a projection stereolithography (SLA) 3D printer to rapidly fabricate customized EPTs and fingers with high resolution. The motor integrated hand, called ADEPT (Adaptively Driven via Elastomeric Passive Transmissions), has a mass of ~399 g and a material cost of less than $500.

Results

1. Elastomeric Passive Transmission Design

The elastomeric passive transmission is an intelligent composite which autonomously adjusts its spooling radius for mechanical advantage based on environmental interaction. We tuned the degree of passive adjustment through the geometry of the EPT. Each EPT is a composite consisting of both high (H-) and low (L-) modulus polyurethanes (PU). The HPU (RPU 70, Carbon, Inc.) serves as the core of the EPT ensuring a rigid connection to the motor shaft. This core is surrounded by a ring of LPU (EPU 40, Carbon, Inc.) struts which give the system its dynamic spooling radius. Our EPTs are printed in two parts and bonded together during the final curing stage (Fig. 1b, c, d). We used Continuous Liquid Interface Production (CLIP) projection stereolithography (31) to rapidly print and iterate the design of both components of the EPT (Video SV1). 3D-printing the EPTs allows us to reduce manual effort in fabrication, and to enable inexpensive, low volume production of personalized parts compared to alternative manufacturing approaches (32).

EPTs can be used with any tendon driven actuation system by spinning with their motor shaft and winding a tendon around their circumference. Under no tension, the EPT struts are un-deformed and the spooling radius is large for high-speed actuation. As the tension increases, the struts are pulled into the center and the spooling radius decreases passively until an equilibrium between the tendon force and stress in the struts is reached. The spooling radius is minimized, and tension maximized, when the motor reaches its stall torque (τ). The change in spooling radius due to tension, $R_T = R_o - R$, can be solved for using equation 1:

$$T\,cos\left(90° - \frac{180°}{N}\right) = E\pi r^2 \frac{\left(\sqrt{R_T^2+\left(\frac{h}{2}\right)^2}-\frac{h}{2}\right)}{\frac{h}{2}} \cos\left(atan\left(\frac{\frac{h}{2}}{R_T}\right)\right)$$

where R_o is the outer radius and R is the current radius. After the LPU struts contact the HPU inner core, they are compressed, resulting in further reduction of radius modeled by equation 2:

$$R_c = R_i + 2re^{\frac{T_C - T}{R_i E_C w}}$$

In these equations, h is the height of the elastomeric struts, N is the number of struts, R_i is the radius of the inner core, r is the radius of the struts, w is the width of tendon contact with the EPT; these geometric parameters can be seen if Fig. 1. T_c is the tension at which the struts initially contact the core of the EPT, E is the storage modulus of LPU in tension, and E_C is the compressive modulus (Fig. S1). Due to non-linearities in these properties, we approximate E and E_C each as five-part piecewise functions. The calculated results were smoothed with a moving average to simulate using continuous E and Ec. In our model, we define the spooling radius, R, as $R = R_o - R_T$ before the struts come in contact with the rigid core (for $R > R_i + 2r$) and $R = R_C$ after the struts contact the rigid core (for $R < R_i + 2r$).

To assess and compare different EPT designs, we defined two geometric and material property dependent characteristics for the EPTs: (i) SRR_{max}, the maximum spooling radius ratio (SRR), and (ii) SRR_{eff}, the effective SRR in operation with a motor and actuator. The SRR can be viewed as the amount by which an EPT will multiply the stall force of a tendon driven actuator as compared to a rigid spool of the same outer radius.

SRR_{max} is only dependent on the geometry of the EPT and is defined simply by: $SRR_{max} = R_o/(R_i + r)$. SRR_{eff}, on the other hand, incorporates the material properties, the initial change in radius due to the mechanical resistance of the unloaded actuator, F_A, and the maximum change in radius based on the stall torque (τ) of the motor. We define the effective spooling radius ratio as

$$SRR_{eff} = R_{oe}/R_{ie}$$

where the effective outer radius, R_{oe}, is the spooling radius when an unloaded actuator is fully actuated (when $T = F_A$), and R_{ie} is the spooling radius when the motor stalls and can be solved for using equation 1 or 2 with $T = \frac{\tau}{R}$ (Fig. 1e). Ideally, the EPT is stiff enough to resist changes in radius when driving an unloaded actuator and soft enough to allow the motor to cause a large change in radius before stalling.

To evaluate the validity of our mathematical model, we fabricated EPTs with varying SRR_{eff} for experimental testing and named them according to Figure 2a. For example, *EPT 2* has N = 20 struts, r = 0.625 mm, h = 7 mm, and $R_o = 10$ mm. All the EPTs we tested had an $R_i = 2.5$ mm, due to the size of the motor shaft. We compared experimental spooling radius vs. tendon tension to the theoretical model (Fig. 2b).

2. Parametric Model

To better understand how changes in geometry effect the performance of our EPTs, we created a parametric model using equations 1 and 2. We simulated various EPT geometries by varying parameters N, h, r, R_o and holding $R_i = 2.5$ mm, $\tau = .19$ N $-$ m, $F_A = 2.5$ N, and the LPU material properties constant. We evaluated how changes in these parameters affect SRR_{eff}, strut tensile strain (Fig. 3), and stress (Fig. S2). We were interested in the strain and stress due to their impact on the fatigue life of the EPTs (further discussed in Section 3). We determined the experimental strut strain, strut stress, SRR_{eff}, R_{ie}, and R_{oe} of each EPT geometry from Figure 2.

The best EPT for a given F_A and τ would be the one with highest SRR_{eff} while having the lowest strut strain and stress. Based on our model, we see that we can increase the stiffness of an EPT by decreasing the height of the struts (h), increasing the number of struts (N), or increasing the strut radius (r), however, changing each of these parameters has inherent limitations. Decreasing the height of the struts increases the strain, thus reducing the fatigue life of the device. Increasing the number of struts causes overcrowding when closer to the inner core (not modeled), thus increasing R_{ie} and reducing SRR_{eff}. Increasing strut radius also increases R_{ie}, again reducing SRR_{eff}. Increasing R_o has the potential to increase SRR_{eff} (given a strong enough motor), but this increases strut strain, unless the increase in R_o is matched with an increase in h. To maintain low strains for fatigue life, the ratio between R_o and h should be kept constant. From this model we chose to use *EPT 2* as it has the highest SRR_{eff} with the proper volume for use in our ADEPT hand.

3. EPT Fatigue Life

The benefits of elastomeric transmission systems are that they can be 3D printed quickly (50/hour), cheaply (< \$1/part), and in many compact form factors. The elastomers we presently use to print EPTs, however, are subject to wear from repeated use leading to failure in the form of LPU strut breakage. Though they remain functional for actuation, the SRR of an EPT decreases with each broken strut. To evaluate the fatigue life of the

EPT as a whole, we define failure as a 2.5% drop in SRR_{eff}, which, based on our model, corresponds to four broken struts in the EPTs we measured for fatigue life.

We conducted a series of cyclic loading tests to quantify and extend the fatigue life of EPTs. We found that the cycles to failure, C_f, for *EPT 2* in high-speed mode ($T \sim F_A + 1$ N) was 2,497 ± 1,115 cycles and that failures occurred at the points of bending in the LPU (Fig. S3) not in contact with the tendon. This indicates that failure is not caused by frictional abrasion of the constituent LPU but simply from accumulated plastic deformation due to crack propagation, meaning the fatigue life can be increased by reducing strain of and stress applied to the struts.

When cycled to maximum force (high-force mode), *EPT 2* demonstrated a reduced fatigue life of $C_f = 49 \pm 27$ cycles. In high force mode, the maximum stress encountered by the EPT is $\sigma_{max} \sim \frac{T}{wR} \sim 10\ MPa$, (33) corresponding to a strain of $\varepsilon \sim 270\%$ (Fig 4a). Cyclic testing of LPU samples in tension (Fig. 4b) at $\varepsilon \sim 270\%$ resulted in $C_f = 32 \pm 15$ cycles—verifying the wear mechanisms of the EPT in high force mode.

Using this information, we improved the service life of the EPT using two mechanical design changes intended to decrease local stresses and strains on the struts. It is important to note that while these stress reductions increase fatigue life, they also decrease SRR_{eff}. The first change, doubling the tendon diameter causes a drop in $SRR_{Eff} = 2.63 \pm 0.07$ while increasing the cycles to failure to $C_f = 2{,}743 \pm 146$ cycles and $C_f = 200 \pm 32$ cycles in high-speed mode and high-force mode, respectively. The second change was to extend the LPU section from the struts towards the core at the top and bottom of the EPT. We did this to simulate having a taller EPT because our parametric model shows that increasing the height can lower the strain to increase the fatigue life while maintain a small form factor. This change, in conjunction with the increased tendon diameter (Fig. S4), lowered the $SRR_{Eff} = 2.18 \pm 0.07$ and led to a small increase in fatigue life in high-speed mode, $C_f = 3{,}140 \pm 907$ cycles, and a significant increase in high-force mode, $C_f = 458 \pm 167$ cycles. The high-force fatigue life of the EPTs incorporating these changes are consistent with the cyclic performance of LPU in tension at or below $\varepsilon = 175\%$ ($C_f = 274 \pm 40$ cycles).

Though these reductions in stress increased the fatigue life of EPTs, the most drastic improvements were due to the use of a new, limited release LPU material (EPU 41, Carbon Inc.). This material, in conjunction with the stress reduction techniques discussed previously, led to high-speed fatigue life of more than 25,000 cycles (single strut breakage, .3% drop in SRR_{eff}) and high-force fatigue life to C_f = 1991±153 cycles while maintaining a higher SRR_{eff} of 2.5 ±0.02 due to the increased storage modulus (34).

4. EPT Driven Actuator Performance

We conducted two sets of experiments to characterize the performance of our EPT in a tendon-driven finger actuator. First, we measured the maximum force we could apply at the tip of the finger, FF (Fig. 5a). In the second experiment, we measured the closing speed of the fingertip, Γ(Fig. 5b), when its motion is unimpeded. Γ is the average radial velocity about the synthetic metacarpophalangeal joint according to Belter et al. (35). In each of these experiments, we compared *EPT 2*, to an array of rigid spools with different radii (Fig. 5c). Our *r* = 10 mm EPT closed the finger in 450 ms ($\Gamma \sim 180$ degrees sec^{-1}) — the same maximum flexion speed as a *r* = 9 mm rigid spool, and delivered a maximum fingertip force, FF~32 N, equivalent to an *r* = 3 mm rigid one. This shows that our EPT achieves the high speed benefits of a large radius spool while still delivering the high force of a small radius one.

5. Design of the ADEPT Hand

The ADEPT hand is composed almost entirely from 3D-printed components (Fig. 6a). Each finger is printed from LPU with three living hinges, thickness ~0.5 mm, and three chambers for integrating the ETA sensors. The living hinges of the thumb are oriented at 25° from the horizontal plane to promote twisting toward the palm upon actuation (Fig. 6b). The thumb also contains a mesh at its base which allows us to emulate the movement of a ball joint using a single elastomeric component. The fingers are driven by inexpensive geared DC motors (~$15; 298:1 Micro Metal Gearmotor HP 6V, Pololu Corporation) with the exception of the thumb, which is driven by two motors—one for each of its two active degrees of freedom. The motors are powered by a 2-cell (7.4 Volts), 500 mAh Lithium Polymer battery which also resides in the palm of the hand. Although the motors are classified as 6-Volt motors it is common practice to drive 6-Volt motors as high as 9 Volts for prosthetic applications (36).

The palm of the hand consists of an inner plate and an outer casing (both printed with HPU). The inner plate secures the six motors and associated electronics; the outer casing has an LPU skin on the palm to increase its softness and friction for grasping. With the 2-cell battery, the hand has a mass of 399 g (365 g not including the battery)—less than the mass of the average human hand (~400 g).

In addition, we integrated force and proximity sensing into each finger of our ADEPT hand for improved control. Extrasensory Tactile Array (ETA) sensors, based on work from Patel and Correll (38), are composed of flexible printed circuit boards with three infrared proximity sensors covered in a layer of silicone rubber. By changing the type of coating rubber, we can adjust the behavior of a sensor on the ETA. In this work we demonstrate two types of sensors: (i) Proximity and (ii) Tactile. The Proximity ETA is created by coating the optical sensors with a transparent silicone (Solaris; Smooth-on, Inc.) and assists with controlling the timing of a grasp. The transparent silicone leads to a sensing range of d ~80 mm but suffers from poor force tracking under 20 N due to a non-monotonic relationship between sensor reading and force in this range (Fig. S5, S6). The Tactile ETA sensor is coated with a more opaque silicone (EcoFlex 35 FAST, Smooth-On, Inc.) which leads to a shorter sensing range (d ~16 mm) but improved force tracking. In combination with the series elasticity of the EPT, ADEPT has the capacity for high-fidelity force control which is more desirable than position control in unstructured environments (37). We dropped a 150 g ball onto the tip of a finger actuator (Fig. 7a; Video SV2) and use the ETAs to measure proximity and force of the ball. Fig. 7b and 7c help visualize the seamless transition between the Proximity (Fig. 7b) and Tactile (Fig. 7c) sensors in the ETA. In this figure you can clearly see the bouncing of the ball including the height of each bounce, the distinct instances of contact, and the force upon contact with the finger. This extrasensory perception allowed our ADEPT hand to catch a thrown ball (further discussed in section 6).

6. Speed and Force Demonstrations

With the help of the ETA sensors and the speed afforded by the EPT, the ADEPT hand is capable of catching objects thrown to it (Fig. 8a; Video SV3). In these demonstrations, the hand catches and holds multiple objects including a 20 g stress ball and a 12 oz soda can (empty weight ~13 g). The ETA sensors detect the approaching object at d ~7.5 cm which triggers closing of the fingers and thumb around the object. Along with the flexion speed necessary to catch a thrown ball, the ADEPT hand has the strength to crush aluminum cans (Fig. 8b; Video SV3) and hold heavy objects such as a wrench (900 g; Video SV3). Without the EPT, our tendon-driven hand would either have the speed to catch a ball or the strength to crush a can, but it would not be capable of both.

Discussion

The Elastomeric Passive Transmission has allowed us to create actuators with a 2-3x increase in output force while maintaining maximum flexion speed comparable to a large rigid spool. The simplicity of our EPT allows it to be small, lightweight, and inexpensive to manufacture with limited manual effort. It also allows us to quickly adjust the size and SRR_{eff} of each device to work with a variety of different motors. Though we have focused on SRR_{eff} and fatigue life as the metrics of interest in the evaluation of our EPTs, it is important to note that efficiency is another key metric which is outside the scope of this work.

Based on our cyclic experiments we determined that EPT failure is caused by crack propagation (39) in the LPU struts due to cyclic loading. One short term solution to this issue is to simulate muscle fatigue by limiting the number of high force cycles the hand can perform in a day (40). Another approach is improving the mechanical design to reduce stress concentration for improved resilience. The root cause for cyclic failure of the EPTs is attributed to the low fatigue life of current SLA 3D printed elastomers. As the material library for SLA printable elastomers grows (41, 42), using material with improved fatigue properties will increase fatigue life as exhibited when using EPU 41.

We used our inexpensive EPTs to solve a persistent engineering contradiction in powered prosthetic hands—simultaneous high speed (180°/s) and high force (32 N) precision grasping, similar to the abilities of a human hand performing daily activities (200°/s; 96 N) (36). Due to the compact form of the transmission system, and design freedom of stereolithography 3D printing, we were able to co-design the batteries, motors, and tendons to be contained within the form of the hand while weighing less than 400 g. In comparison, the BeBionic prosthetic, as one example, locates the batteries outside of the hand and weighs ~500 g (36). By incorporating EPTs into our 3D-printed ADEPT prosthetic hand, we have demonstrated one of many promising use cases for our passively adaptive transmission system. We believe these benefits could also expand the capabilities of actuators in other areas such as active tendons (33,43), soft exosuits (44-47), and bio-inspired mobile robots (48-50).

Materials and Methods

Fabrication of EPTs

We generated the CAD files for our EPTs using Fusion 360 (Autodesk, Inc). We printed the HPU cores and LPU struts separately using projection stereolithography (M1, Carbon, Inc.). After cleaning the two parts, we inserted the HPU cores into the LPU struts and coated the seams with a thin layer (~0.5 mm) of liquid LPU resin and was cured for 15 seconds with UV light (365 nm; ECE 5000 Flood, DYMAX, Inc.). After UV curing the EPTs were thermally cured at 120 °C for 8 hours to produce an HPU/LPU composite.

Fabrication of the ADEPT Hand

To fabricate the ADEPT hand, we designed the components using Fusion 360 and printed them with projection stereolithography. The motors were secured inside the palm with compression fitting straps (LPU). Each motor was driven by a DC motor driver breakout board (BD65496MUV, Pololu Corporation). The current draw of each motor was measured with high-side current sensor breakout boards (INA 219 High Side DC Current Sensor Breakout Board, Adafruit Industries, LLC). These motor drivers and current sensors were controlled by a microcontroller breakout board (Feather 32u4 Bluefruit LE, Adafruit Industries, Inc.). The microcontroller, motor-drivers, and current sensors were powered by a 1-cell (3.7 V) LiPo battery (LP402025, PKCELL Battery Co.), while the motors were powered by a separate 2-cell (7.4 V) LiPo (2S20C-500, DLG Electronics Technology Co.). After soldering and securing the electronics to a custom designed and printed plate in the palm (HPU), we slid the EPTs onto the motor shafts and the fingers and thumb into their respective recesses. In the next step, we threaded the Kevlar® threads (KEV138NATL01B, Weaverville Thread, Inc.) through channels in the fingers and palm and tied them off at their EPT (one tendon thread per EPT). Finally, we screwed the front and back casing to the plate of the palm. The back casing was printed with HPU and the front casing was composed of HPU cured to an LPU lattice and membrane to promote friction and grasping.

Spooling Radius vs Tension and Spooling Radius Ratio Experiments

To measure the relationship between tendon tension and spooling radius, we connected the EPTs to a 298:1 gear motor (Micro Metal Gearmotor HP 6V, Pololu Corporation). For each measurement, we tied a tendon between the EPT (the tendon was wound once around the EPT without deforming the EPT struts) and a push/pull force gauge (Torbal FC200, 200±0.05 N). We ran the motors at 7.5 Volts and captured images of the deformed EPTs at stall (maximum torque). We analyzed each of the images using ImageJ to determine the spooling radius of the EPT. We conducted seven trials for each of the EPT and motor combinations and averaged the data to generate the data points in Figure 2b. The standard deviation for spooling radius did not exceed 0.1 mm for any of these data points. The standard deviation of the measured force did not exceed 0.5 N except for the highest force data points for *EPT 1* (SD = 1.68 N) and *EPT 2* (SD = 3.22 N).

The data from the spooling radius vs tension experiments when the motor stalled was used for the effective inner radius (R_{ie}) in our effective spooling radius ratio (SRR_{Eff}) measurements (Fig. 2b). The effective outer radius (R_{oe}) was determined by driving a finger actuator with our 298:1 gear ratio motor and each of our three EPT geometries. We captured images of the EPT deformation when the unloaded finger was fully actuated and used ImageJ to determine the effective spooling radius. The reported values for SRR_{Eff} were generated by dividing the averaged data for R_{oe} over seven trials by the averaged data for R_{ie} over seven trials.

Modeling of Spooling Radius vs. Tension

When $R > R_i + 2r$, using Matlab, we calculate the tension required to get to the end of the strain range using a specific storage modulus seen in Table 1. If that tension is higher than the tension $\left(T = \frac{\tau}{R}\right)$ provided by a stalled motor at that radius, then we solve for R_t with equation 1 using that E. Otherwise, add that tension to equation 1 and repeat with the next strain range and E until R at stall is found. If the model begins compression ($R < R_i + 2r$) but has not stalled, using the piecewise E_C found in Table 2, we set T_c equal to the tension required to get to the start point (either the beginning of compression for the first E_C or the tension required to get to the next strain range for the following E_C) and $2r$ to be the R at the start of the strain range with R_i subtracted. Just like the tensile section, the limits are tested and equations solved until stall torque is reached.

Fatigue Testing of EPTs

The fatigue life of EPTs tested while driving a finger actuator. Each fatigue life data point represented included n = 3 EPT specimens. The number of cycles were counted until the fourth LPU strut was broken. Tensile testing of LPU was conducted with a Zwick/Roell tensile testing machine. Fatigue life data of LPU consists of n = 3 data points with the exception of cyclic testing at $\sigma = 80\%$ which includes only n = 2 data points. There is only n=1 EPU 41 high-speed and n=3 high-force tests.

Force Characterization of EPT-Driven Finger Actuators

To gather maximum fingertip force data for our finger actuators, we applied 7.5 Volts to the motor (298:1 Micro Metal Gearmotor HP 6V, Pololu Corporation) driving the actuator using a DC power supply (1745A, B&K Precision Corporation) until the motor stalled. While the motor was running, we measured the fingertip force with a 5-Kg loadcell (Load Cell Sensor 0-5 kg, UXCELL). The loadcell output was amplified using an amplifier breakout board (Sparkfun Loadcell Amplifier – HX711, Sparkfun Electronics, Inc.). The amplified signals were read using an Arduino Uno (Arduino AG). The highest force value for each experiment was recorded. The reported maximum fingertip force values are the average of ten experiments.

Speed Characterization of EPT-Driven Finger Actuators

To measure the flexion speed of our EPT-driven fingers, we mounted them to a 3D-printed testing rig with an attached infrared proximity sensor (VCNL 4010, Vishay Intertechnology, Inc.). A command from the user to actuate the finger also started a timer within the microcontroller. We determined a threshold value of the IR sensor which was associated with full flexion of the finger. When this threshold value was exceeded, the microcontroller stopped the timer. We captured images (EOS REBEL T3i, Canon U.S.A., Inc.) of the finger in the unactuated state and used imageJ to measure the angle between each of the joints in the finger. The reported flexion speed is the number of degrees traversed by the MCP joint (determined via imageJ) divided by the closing time reported by the microcontroller. The reported maximum finger flexion speeds are the average of ten experiments.

ETA Sensor Demonstrations

We compared the force and proximity readings of our ETA sensors by placing the end of a finger actuator on top of a push/pull force gauge (Torbal FC200, Scientific Industries, Inc.) with the ETA sensor facing up. We dropped a 150 g ball (Rubber Lacrosse Ball, Dick’s Sporting Goods, Inc.) from a height of 60 cm through a clear acrylic tube and filmed the ball bouncing on the finger with a high-speed camera (Phantom Miro 310, Vision Research, Inc.). We analyzed the frames of the resulting videos using ImageJ to determine the height of the ball at each time step.

The ETA sensors were calibrated using the same method as the ball drop characterization—we held the 150 g ball above the sensor at known heights (using our camera and ImageJ) and pushed the ball against the sensor with known forces (using our push/pull force gauge). We used Origin 2016’s (OriginLab, Inc.) curve fitting functions to determine the mapping between raw sensor data and reported measurements (distance and force). We found that the Asymptotic1 Exponential function ($y = a - bc^x$) was best suited for the proximity calibration of our sensors.

List of Supplementary Materials

Figure S1. Uniaxial Compressive Performance of LPU.
Fig S2. 2D Parametric Model Graphs.
Fig S3. Strut Failure Due to Cyclic Bending in the EPT.
Fig S4. EPT with Soft Caps in High-Speed Mode (left) and High-Force Mode (right).
Fig S5. ETA (Tactile) Force Tracking.
Fig S6. ETA (Proximity) Force tracking.
Video SV1. EPT Printing
Video SV2. Finger Sensor - Ball Drop Test
Video SV3. ADEPT Hand Demos

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Acknowledgments

The authors would like to thank Dr. Richard Weir and Dr. Jacob Segil for their feedback and support during this project. The authors would also like to thank the Cornell Center for Materials Research and Professor Meredith Silberstein.

Funding: Research reported in this publication was supported, in part, by the National Center for Advancing Translational Sciences of the National Institutes of Health under Award Number TL1TR002386. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. This research was also supported by the Air Force Office of Scientific Research under Award Number FA9550-18-1-0243, and the Office of Naval Research Young Investigator Award under Award Number N00014-17-1-2837. This work made use of the Cornell Center for Materials Research Shared Facilities which are supported through the NSF MRSEC program (DMR-1719875).

Author contributions: R.F.S. supervised the research, designed experiments, and edited the manuscript. K.O. conceived the EPT, designed and conducted experiments, and drafted the manuscript. P.X. designed and conducted experiments, data analysis, and theoretical modeling. D.L. created and assembled the ADEPT hand, designed and conducted experiments, and edited the manuscript. C.A., and H.Y., and M.F.X. conducted experiments and conducted data analysis. L.W. assisted in the design of the ADEPT hand.

Competing interests: The authors declare that they have no competing financial interests. K.O. and R.F.S. are listed as inventors on a U.S. provisional patent application (62/560,434) submitted by Cornell University that covers fundamental principles and designs of the Elastomeric Passive Transmission.

Data and materials availability: All data needed to evaluate the conclusions in this paper are present in the paper or the Supplementary Materials. Contact R.F.S. for materials.

Figure and Table Captions

Fig. 1. EPT Operation and Manufacturing. (**A**)Increasing tendon tension causes a reduction in spooling radius of the EPT leading to higher output forces. EPTs are manufactured via projection stereolithography in two parts, (**B**) a rigid core and (**C**) a ring of elastomeric struts. (**D**) The two parts are cured together to form a polyurethane composite. (**E**) Close up of the EPTs spooling in high-speed mode (top) and high-force mode (bottom).

Fig. 2. EPT Characterization. (**A**) Six EPTs with different geometries. (**B**) The spooling radius of the six EPTs as a function of tendon tension (solid symbols) compared with their theoretical values (dashed lines).

Fig. 3. Parametric Model. SRR_{eff} and strut strain when varying (**A**) the number of struts from 10-30, (**B**) the strut radius from .5 to 1 mm, (**C**) the height from 5-15 mm, and (**D**) outer radius from 5-30 mm. The dotted lines are the model with the constant parameters shown in the legend and the symbols representing experimental data for the six EPT geometries.

Fig. 4. LPU Fatigue Life. (**A**) Tensile strain performance, to failure, for seven samples of LPU. (**B**) Cyclic tensile loading and unloading performance of LPU at strains corresponding to the colored circles in part A.

Fig. 5. EPT Driven Finger Performance. (**A**) A comparison of the unloaded finger closing time and (**B**) maximum fingertip force between an EPT and rigid spools. (**C**) The EPT performance outside the Pareto Front for speed and force generated by rigid spools of varying radius.

Fig. 6. The ADEPT Prosthetic Hand. (**A**) A rendering of the ADEPT hand with its main components listed. (**B**) Time-lapse image of thumb flexion demonstrating its angled joints.

Fig. 7. ETA Sensor Demonstration. (**A**) Finger actuator with tactile and proximity ETA sensors labeled. (**B**) Calibration curve for the ETA (Tactile) sensor, normalized signal intensity is the ratio of the signal reading to the maximum value of the sensor (16-bit unsigned integer). (**C**) Calibration curve for the ETA (Proximity) sensor. (**D**) Time-lapse depicting the motion of a ball dropped onto ETA sensors to demonstrate force and proximity sensing. (**E**) Results of a single ball-drop experiment for an ETA (Tactile) sensor. (**F**) Results of a separate ball-drop experiment using an ETA (Proximity) sensor.

Fig. 8. Speed and Force Demonstration. (**A**) Time-lapse image of the ADEPT hand catching a thrown ball. ETA sensors detect the ball approaching at ~7.5cm and trigger closing of the hand. (**B**) Demonstration of the ADEPT hand crushing an aluminum can.

Table 1. Piecewise tensile storage modulus used in model for each strain range

Table 2. Piecewise compressive modulus used in model for each strain range

Tables

1)

Strain range	$\varepsilon \leq 10\%$	$10\% \leq \varepsilon \leq 18\%$	$18\% \leq \varepsilon < 25\%$	$25\% \leq \varepsilon < 50\%$	$50\% \leq \varepsilon$
E (MPa)	10.6	7.33	4.88	4.77	3.00

2)

Strain range	$\varepsilon < 4\%$	$4\% \leq \varepsilon < 6\%$	$6\% \leq \varepsilon < 10\%$	$10\% \leq \varepsilon < 50\%$	$50\% \leq \varepsilon$
E_C (MPa)	0.030	1.91	3.90	15.1	30.0